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Is groundwater response timing in a pre-alpine catchment controlled more by topography or by rainfall?

Rinderer M.¹, van Meerveld H. J.¹, Stähli M.², Seibert J.^{1,3}

¹ Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland

² Swiss Federal Research Institute WSL, Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland

³ Department of Earth Sciences, Uppsala University, SE-752 36 Uppsala, Sweden

Corresponding author: michael.rinderer@geo.uzh.ch

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Abstract

Groundwater levels in steep headwater catchments typically respond quickly to rainfall but the timing of the response may vary spatially across the catchment. In this study, we investigated the topographic controls and the effect of rainfall and antecedent conditions on the groundwater response timing for 51 groundwater monitoring sites in a 20 ha pre-alpine catchment with low permeability soils. The median time to rise and median duration of recession for the 133 rainfall events were highly correlated to the topographic characteristics of the site and its upslope contributing area. The median time to rise depended more on the topographic characteristics than on the rainfall characteristics or antecedent soil wetness conditions. The median time to rise decreased with Topographic Wetness Index (TWI) for sites with $TWI < 6$ and was almost constant for sites with a higher TWI. The slope of this relation was a function of rainfall intensity. The rainfall threshold for groundwater initiation was also a function of TWI and allowed extrapolation of point measurements to the catchment scale. The median lag time between the rainfall centroid and the groundwater peak was 75 minutes. The groundwater level peaked before peak streamflow at the catchment outlet for half of the groundwater monitoring sites, but only by 15 to 25 minutes. The stronger correlations between topographic indices and groundwater response timing in this study compared to previous studies suggest that surface topography affects the groundwater response timing in catchments with low permeability soils more than in catchments with more transmissive soils.

1. INTRODUCTION

In steep mountain headwater catchments, shallow groundwater can respond quickly to rainfall because alpine soils are typically thin and gradients are steep (Hammermeister et al. 1982; Penna et al. 2014). These groundwater dynamics play an important role in runoff generation and hydrologic connectivity of the hillslopes to the stream because they exert a strong control on lateral subsurface stormflow (Lowery et al. 1982; Wilson et al. 1990; Weiler et al. 2005). Identifying the factors that control the spatial variability in shallow groundwater dynamics will, therefore, improve our understanding of how catchments function (McGlynn & McDonnell 2003; McDonnell et al. 2007).

Because the magnitude and timing of the groundwater response to rainfall are controlled by different variables, such as topography and soil- and bedrock properties, the occurrence of (perched) groundwater can be very patchy and the response to rainfall can be highly variable (Fannin et al. 2000; Bachmair & Weiler 2012). Previous measurements of groundwater levels across hillslope transects and catchments have revealed that the timing and magnitude of the water table response is related to dynamic factors that vary with time, such as rainfall amount and intensity and antecedent conditions (Scanlon et al. 2000; Dhakal & Sullivan 2014), and static factors, such as landform (Detty & McGuire 2010), distance to the stream channel network (Seibert et al. 2003; Rodhe & Seibert 2011; Haught & van Meerveld 2011), thickness of the soil or the topography of the bedrock (Penna et al. 2014; Tromp-van Meerveld & McDonnell 2006).

The observations reported in the literature are, however, ambiguous with respect to the correlation between groundwater levels and streamflow. In some catchments, groundwater levels close to the stream were well correlated with each other and with discharge, but groundwater levels in upslope locations were not (Haught & van Meerveld 2011; Seibert et al. 2003). The decreasing correlation between groundwater levels and discharge with increasing distance from the stream suggested that upslope areas did not contribute to streamflow during events. Furthermore, sites close to the stream responded prior to streamflow, while the groundwater response in the upslope sites was delayed and more variable. As antecedent soil water content increased, groundwater lag times became shorter and groundwater peaks preceded streamflow peaks (Haught & van Meerveld 2011). Other studies have shown that the runoff response preceded the groundwater response (Penna et al. 2014), which at a first glance is contradictory to the common perception of how groundwater contributes to streamflow (Sklash & Farvolden 1979). Yet other researchers have shown that groundwater response times were shortest in the upper parts of the hillslopes and related this to the spatial distribution of soil thickness and the topography of the soil-bedrock interface (McDonnell 1990; Rodhe & Seibert 2011; Penna et al. 2014; Tromp-van Meerveld & McDonnell 2006). Yet for other catchments there was no correlation between the duration of transient saturation and the distance from the stream (Lana-Renault et al. 2014) and no relation between peak groundwater level and topographic position (Dhakal & Sullivan 2014). However, the instrumentation in some studies was limited to the interface between the hillslope and the riparian zone and results may therefore not be

representative for catchment-wide groundwater dynamics (Anderson & Burt 1978; Moore & Thompson 1996).

These partly contradictory observations reflect site-specific settings and have made it difficult to generalize these findings or to transfer them to other catchments.

Nevertheless, attempts were made to explain groundwater responses based on catchment characteristics such as topography, soil properties or vegetation. Under wet conditions (Anderson & Burt 1978; Burt & Butcher 1985; Lana-Renault et al. 2014), steep terrain or distinct morphology (Haught & van Meerveld 2011; Rodhe & Seibert 2011) or shallow groundwater tables (Troch et al. 1993; Seibert et al. 2003), variability in groundwater responses were related to topography. Under dry conditions (Detty & McGuire 2010), flat terrain (Barling et al. 1994), and for permeable soils (Seibert et al. 1997; Dhakal & Sullivan 2014; Anderson et al. 2010), the relation between groundwater response and topography was not clear. In catchments with transmissive soils, the variability in saturated hydraulic conductivity (Bachmair & Weiler 2012), soil depth (Penna et al. 2014), bedrock topography (McDonnell 1990; Tromp-van Meerveld & McDonnell 2006), vegetation and landuse (Lana-Renault et al. 2014) and snowmelt patterns (Smith et al. 2014) could explain the variability in groundwater response better than topography.

Rainfall input and antecedent conditions are also important controls on shallow groundwater responses. Groundwater peak duration and response amplitude were larger during the wet season and during events that exceeded a certain rainfall threshold in the Hubbard Brook Experimental Forest catchment in the New Hampshire, USA (Detty & McGuire 2010). On the contrary, in the Black Forest in Germany groundwater responses were small and slow during wet conditions in fall, winter and spring and affected predominantly the footslopes, while during dry summer conditions the groundwater responses were quicker, more variable and occurred across the whole hillslope (Bachmair et al. 2012). For other hillslopes or catchments, the percentage of groundwater wells that showed a response during individual rainfall events was correlated to total event precipitation and storm duration but not to rainfall intensity and antecedent conditions (Penna et al. 2014; Dhakal & Sullivan 2014; Fannin et al. 2000).

Despite the knowledge gained by these hillslope-scale studies at sites with transmissive soils, we still know little about catchment-scale groundwater dynamics in steep mountain environments with less permeable soils. One might expect the groundwater levels to be closer to the surface and to be more responsive to rainfall because of the lower storage deficit, low drainable porosity and low hydraulic conductivity of the mineral soil. As groundwater levels rise close to the soil surface and into higher permeability soil layers, surface topography might exert a stronger control on the lateral redistribution of water (Hutchinson & Moore 2000). One could therefore expect surface topography to explain a larger fraction of the variability in shallow groundwater responses in a catchment with low permeability soils than for catchments with higher permeability soils. To test this assumption, we analyzed the timing of the groundwater responses in a subalpine headwater catchment in Switzerland and correlated it to topographic indices and rainfall and antecedent wetness conditions.

In particular, we address the following questions:

1. To what extent does topography govern the frequency and timing of the groundwater response, in particular the start of the groundwater level rise, the timing of peak groundwater level and the duration of the recession?
2. Is there a rainfall threshold for groundwater response initiation and if so, does this threshold depend on the topography?
3. How do antecedent precipitation and rainfall intensity influence the timing of the groundwater response?

2. METHODS

2.1. Study Catchment

The 20 ha study catchment is located in the Alptal, a pre-alpine valley about 40 km southeast of Zurich, Switzerland (Fig. 1). The catchment is steep with an average slope of 35 % and extends from 1270 m asl. to 1650 m asl. Mean annual precipitation in the region is 2300 mm/year, of which 30 % falls as snow (Feyen et al. 1999). The catchment is normally snow-covered between December and May. The largest and most intense rainfall events occur typically between June and September. The catchment is characterized by distinct small-scale topography with hollows and ridges and a dense natural drainage network (205 m/ha). The main channel close to the catchment outlet has 2 to 4 m deep banks on both sides but the other streams are not deeply incised. A distinct riparian zone is missing in this study catchment. The Topographic Wetness Index (TWI = $\ln(a/\tan\beta)$ where a is the upslope contributing area per unit contour length [m^2] and β is the local slope gradient [$^\circ$]; (Beven & Kirkby 1979) varies between 2 and 14 (median TWI: 5). “Dry” sites in this catchment are defined as TWI < 4 (19% of the catchment) and “wet” sites as TWI > 6 (32 % of the catchment). Moor landscapes and wet grassland areas are common in hollows and the flatter parts of the catchment (ca. 7 ha), while on steeper slopes and ridge-sites open coniferous forest grow (*Picea abies* L. with an understory of *Vaccinium* sp.; ca. 11 ha) (Hagedorn et al. 2000). Parts of the upper catchment (ca. 2 ha) is seasonally used for grazing cattle. In wet depressions, where the water table is persistently close to the soil surface, the soils are mollic Gleysols with a topsoil high in carbonate. The mineral soil consists of a permanently reduced Bg horizon, with typically 43 % clay, 42 % silt and 15 % sand (Schleppi et al. 1998). At the ridge sites, where the water table is normally more than 0.40 m below the soil surface, the soils are umbric Gleysols with an oxidized Bw horizon (49 % clay, 46 % silt and 5 % sand) (Schleppi et al. 1998; Hagedorn et al. 2001). Soil depth varies between 0.5 m at ridge sites to more than 2.5 m in depressions. The bedrock consists of a poorly permeable clay-rich Flysch with calcareous sandstone and argillite and bentonite schist layers (Mohn et al. 2000).

2.2. Field Measurements

Groundwater levels were measured continuously at 51 locations across the study site between September 2010 and the end of November 2012. The monitoring sites were selected based on a stratified random sampling approach using the TWI in seven nested sub-catchments (C1 to C7, ranging in size from ~0.2 ha to 20 ha; Fig. 1). This procedure guaranteed representative sampling of the range of topographic positions, soil types and vegetation in the catchment (8 ridge site, 22 midslope- and 21 footslope- or depression locations; 25 mollic Gleysol sites and 26 umbric Gleysol sites; 20 forested sites and 31 grassland sites). At each site, a borehole was manually drilled down to refusal (mean well depth: 1.06 m, min: 0.46 m, max: 2.16 m). The boreholes were fitted with a 4 cm diameter PVC pipe, screened over the full length up to 10 cm below the surface and

backfilled with coarse filter sand. The filter pack was sealed with bentonite and plastic foil 5-10 cm below the surface to prevent water entering the well from the soil surface. Water levels were measured in the wells at a 5 min interval during summer (May to December) and a 10 min interval during winter using Odyssey capacitance water level loggers (Dataflow Systems Pty Limited). Groundwater level measurements were checked manually approximately every 2 to 3 months and corrected for a potential offset.

Stream stage at the outlet of the 20 ha study catchment (C7 in Fig. 1) was measured in a natural cross-section every 5 minutes from May to December 2011 and May and December 2012 using pressure loggers (DL/N 70 by STS, Sensor Technik Sirmach AG). Changes in the natural cross-section were documented monthly and deemed to be minor for the study period. Salt dilution measurements during seven events of different magnitude and a low flow period were used to determine the rating curve for the cross section. The rating curve covers 58 % of the range of water levels recorded during the study period and had to be extrapolated for only 1 % of the total study period. The extrapolation is not considered to have a major impact on the results of this study as it mainly affects the size of the peakflows and not the timing of the response.

Precipitation and air temperature were recorded every 10 minutes at a permanent meteorological weather station 1 km from the experimental catchment at 1219 m asl.. Barometric pressure for the correction of the stream stage measurements was recorded every 5 minutes. There was no reliable information on the spatial pattern of precipitation in the catchment but due to its size we expect the differences to be small.

2.3. Rainfall Event Characteristics

Rain events were defined as events exceeding 5 mm of total rainfall (the median daily rainfall of all days with rain) or had a maximum rainfall intensity > 2 mm/10min (the 85 % quantile), separated by at least 2 hours without rainfall. Events during winter when the catchment was snow-covered (i.e., between December 1st, 2010 and April 12th, 2011 and between December 1st, 2011 and May 21st, 2012), were excluded from the analyses. The total rainfall during the 133 events that were analyzed was 3027 mm or 93 % of the total rainfall during the snow-free period of the two years considered. The selected rainfall events differed considerably in mean and maximum rainfall intensity, total amount of rainfall, event duration and antecedent wetness conditions and were therefore subdivided into four rainfall event types: *Type 1a*: low-intensity/dry antecedent conditions, *Type 1b*: low-intensity/wet antecedent conditions, *Type 2a*: moderate-intensity/dry antecedent conditions, *Type 2b*: moderate-intensity/wet antecedent conditions. The class breaks were set at an event-average rainfall intensity of 1.8 mm/h and a 3 day sum of antecedent precipitation of 10 mm. These breaks reflect the mean event rainfall intensity that caused a water level response for at least 10 % of all sites (10 % quantile) and the median of the 3 day sum of antecedent precipitation. This classification resulted in roughly 30 events in each class (Tab. 1). Differences in event characteristics between the event classes were tested for statistical significance using the Mann-Whitney test with adjusted p-values based on the Bonferroni method.

2.4. Groundwater Response Time Characteristics

During a typical rainfall event, the groundwater response can be divided into several characteristic phases (Fig. 2, Tab. 2). First, there is a delay between the onset of rainfall and the start of the groundwater level rise. In this study, we denote this as the *time to rise* (t_{rise}) and define it as either the first time step after the beginning of a rainfall event with a positive slope, or the time step with the largest change in groundwater level if the groundwater level was already rising at the start of the rainfall event, which was sometimes the case under very wet antecedent conditions. The sum of rainfall that fell between the start of the rainfall event and t_{rise} is referred to as P_{rise} . Groundwater responses with an absolute rise smaller than the accuracy of the water level loggers (~ 0.5 cm) were considered as no response. Surface saturation prior to an event occurred occasionally at 12 hollow sites (2 events on average); for these it was still possible to detect a response.

After the start of the groundwater response, the groundwater level rises to its maximum. For the Alptal catchment this period lasts between less than an hour and up to one or two days, depending on the type of rainfall event. We defined the *time to peak* (t_{peakP}) as the time lag between the centroid of each rainfall event (i.e., the time at which 50 % of total rainfall had fallen) and the time that the groundwater level had risen to 95 % of the maximum rise in groundwater level for each event. We used 95 % of the absolute rise (i.e., 95 % of the difference between the groundwater level at the time of first response and the peak groundwater level; see Fig. 2) because it was considered a more robust measure than the peak groundwater level. This was especially the case for sites where the water level first rose quickly and then continued to rise at a much slower rate.

The groundwater table generally remains high for a certain duration. We denoted this time as the *groundwater peak duration* (t_{dur}), which was calculated formally as the difference between the time of the 95 % of the absolute groundwater level rise on the rising limb and the corresponding time on the falling limb (called 95 % recession; see Fig. 2).

When water input from the soil surface and upslope areas decreases and drainage exceeds the input at the monitoring site, the groundwater level starts to fall. We defined the *duration of recession* (t_{rec}) as the timelag between the time of the 95 % of the absolute rise on the recession limb and the time of the 20 % of absolute rise on the recession limb. The *mean slope of the groundwater recession* (s_{rec}) was defined as the difference between the groundwater level at 95 % and 20 % of the absolute rise on the recession limb divided by t_{rec} .

The timing of the groundwater response was also related to the timing of the streamflow response. We therefore define the *timelag between peak groundwater level and streamflow* (t_{peakQ}), as the timelag between the 95 % of the maximum rise in discharge at the catchment outlet (catchment C7) and the 95 % maximum rise in groundwater level.

Other groundwater response time characteristics were determined as well but are not reported here, as they were either highly correlated to the selected five time characteristics or were not as robust as the selected characteristics. All response time characteristics and rainfall characteristics were automatically determined for all rainfall

events using a script written in R (version 2.14.1; Development Core Team 2005) to guarantee objectivity. The number of events at each site differed because of data gaps (median: 108 events; 25 % quantile: 101 events; 75 % quantile: 121 events; out of a total of 133 events). Because the number of events differed for each well, the relative response frequency for each site was determined as the fraction of events for which a water level response was observed divided by the number of events for which data was available at that site.

2.5. Site characteristics

For the analysis of the topographic controls on the groundwater response timing, we determined several topographic indices for each monitoring site based on an aggregated 6 by 6 meter Digital Terrain Model (DTM) based on LiDAR data (original resolution: 2 by 2 m) with an average point density of 1 point per 2 m². Other resolutions were tested but 6 meter was considered fine enough to capture the morphologic features within the catchment and coarse enough to avoid the effects of micro-topography, which are of less importance for the groundwater table. *Local controls* are site characteristics of the measurement location, while *upslope controls* denote the properties of the upslope contributing area (Rinderer et al. 2014). The local site characteristics selected for this study were: local slope gradient (Tarboton 1997), local curvature (Evans 1980; Travis et al. 1975), TWI (Beven & Kirkby 1979) and soil depth. The upslope site characteristics were the size, mean slope, mean curvature, mean TWI and forest percentage of the upslope contributing area. For the delineation of the upslope contributing area, the triangular multiple flow direction algorithm (Seibert & McGlynn 2007) was applied. All indices were calculated using the open source software SAGA-GIS (Conrad 2007). Additional topographic site characteristics were considered in the analyses but are not reported here as they were either highly correlated with the selected indices or not as robust as the selected characteristics. The forest percentage of the upslope contributing area was determined from aerial photographs.

To quantify the relation between topographic characteristics and the response time characteristics, the Spearman rank correlation coefficient (r_s) was determined for each individual event and for the medians of all events in the four rainfall event types. Some plots show the LOWESS regression curve fitted to the median data values as well. The software R (version 2.14.1; Development Core Team 2005) was used to analyze the data. The 0.05 level of statistical significance was used for all analyses. The Mann-Whitney test was used to determine statistically significant differences between the response time characteristics of the four rainfall event types; the Bonferroni method was used to adjust the p-values.

To account for predictor interactions in explaining the spatial variability in groundwater response, we additionally applied the random forest (RF) approach, a multivariate, non-parametric regression method based on ensembles of classification and regression trees (Breiman 2001). This method recursively stepwise splits a bootstrapped subset of the response variable into more and more homogeneous groups based on predictor variables and their combinations (Breiman et al., 1984). The method allows ranking of the predictors according to their importance in explaining the variability of the response

variable. Multiple RF runs result in more stable results than the stepwise variable selection method. Furthermore, no assumption is made about the data distribution or the functional relationship to be discovered. The approach is also not sensitive to cross-correlations among predictor variables (Strobl et al. 2009). We tested model stability with different settings and based on the smallest error estimate ran 20 RF-runs with different seeds, each consisting of 5000 trees and 2 predictor variables at each split. We called predictors “relevant” if their explanatory power was larger than a predictor with random values (Strobl et al. 2009). The R-package “randomForest 4.6-10 of Liaw and Wiener (2002), was used for this analysis.

3. RESULTS

3.1. Rainfall event characteristics

The low-intensity rainfall events had a median event-average rainfall intensity of 1.1 mm/h (type 1a) and 1.2 mm/h (type 1b), while the moderate-intensity events were characterized by more than twice this median event-average rainfall intensity (3.3 and 2.9 mm/h for type 2a and 2b, respectively). These differences in event-average rainfall intensity were statistically significant. The median average three day antecedent sum of precipitation was one order of magnitude smaller for the rainfall events with dry antecedent conditions (2.1 mm and 1.7 mm, for type 1a and type 2a events respectively) than for the events with wet antecedent conditions (27.9 mm and 22.4 mm for type 1b and type 2b, respectively). This difference was also statistically significant. The four rainfall event types also differed significantly from each other in other characteristic, e.g., the median maximum rainfall intensity during these events and the median duration of the rainfall events (Tab. 1, Suppl. 1). For all characteristics the Inter Quartile Range (IQR) was large, reflecting the considerable variability within the four rainfall event types.

3.2. Relative response frequency

During most rainfall events, the groundwater levels showed a distinct response to rainfall in the majority of the wells. For more than 84 % of all rainfall events at least half of the sites responded but the median relative response frequency was different for the four rainfall event types (Fig. 3). When considering all sites together, the response frequency was 15-20 % lower for the low-intensity rainfall events than for moderate-intensity events and this difference was statistically significant (type 1a: 77 %, type 1b: 71 %, type 2a: 93 %, type 2b: 89 %; Fig. 3). The difference in the response frequency for the events with dry and wet antecedent conditions was small and not statistically significant. However for sites with a TWI < 4 and low-intensity events the median response frequency was more than twice as high for moist than for dry antecedent conditions, which was a statistically significant difference. In general, the response frequency of sites with a TWI < 4 was lower than the response frequency of the other sites..

3.3. Groundwater response timing

3.3.1. Groundwater dynamics

The groundwater response of sites with a low TWI ($\text{TWI} < 4$) was delayed compared to the response of sites with a higher TWI (Fig. 4). The difference was on the order of hours and varied for the individual rainfall events. Sites that responded relatively simultaneously, still showed a different response in terms of the gradient, duration and amplitude of the rise (Fig. 4). Groundwater levels rose to the soil surface, not only for sites with a high TWI (e.g., $\text{TWI} > 6$) but also for sites with an intermediate TWI (e.g., TWI : 4-6). While the water level would normally drop soon after the end of a rainfall event for sites with an intermediate TWI, it would generally stay high for several hours to days for sites with a high TWI (Fig. 4).

3.3.2. Time to rise of the groundwater levels

The groundwater level responded to rainfall within minutes to hours. For half of all monitoring sites the median t_{rise} was less than 35 min but the variability in median response times among sites was large (IQR: 5 – 105 min). The moderate-intensity rainfall events had the shortest median t_{rise} : for half of the sites the median t_{rise} was less than 20 min during the type 2a events and less than 30 min during the type 2b events. During the low-intensity events, half of the sites had a median t_{rise} less than 50 min (type 1a) and 78 min (type 1b) (Tab. 3). The IQR of the median t_{rise} of all monitoring sites was more than twice as large for the low-intensity rainfall events than for the moderate-intensity rainfall events (Tab. 3). The difference in the median t_{rise} between the events with dry and wet antecedent conditions was small and not statistically significant.

The median t_{rise} for the monitoring sites was correlated to the topographic indices. The r_s was highest for the mean curvature of the upslope contributing area ($r_s = 0.82$), TWI ($r_s = -0.81$), upslope contributing area ($r_s = -0.74$), mean TWI of the upslope contributing area ($r_s = -0.66$), and local slope ($r_s = 0.64$). The r_s was lower for the mean slope of the upslope contributing area ($r_s = 0.29$) and the local curvature ($r_s = 0.28$) (Tab. 4). The median t_{rise} was not correlated to forest percentage of the upslope contributing area or soil depth. The median t_{rise} and the variability in t_{rise} decreased with TWI for sites with a $\text{TWI} < 6$. For sites with a $\text{TWI} \geq 6$, t_{rise} was short and decreased only slightly with increasing TWI, or was constant (Fig. 5). The decrease in median t_{rise} with TWI for sites with a $\text{TWI} < 6$ was steeper for the low-intensity rainfall events (type 1a and 1b) than for the moderate-intensity events (type 2a and 2b). The analyses were also performed for the 10% most intense rainfall events ($n=14$; mean event rainfall intensity >4.8 mm/h; 7 events with dry, 7 with wet antecedent conditions) but the relationships were similar to those obtained for the type 2a and 2b events.

The correlation between t_{rise} and TWI was significant for 69 % of the individual events ($r_s < -0.61$ for 25% of the events, $r_s < -0.51$ for 50% of the events and $r_s < -0.29$ for 75% of the events) The frequency of significant correlation between TWI and t_{rise} , as well as

the strength of the correlation did not depend on the rainfall characteristics, antecedent conditions or season.

The results of the RF regression of t_{rise} and the selected predictor variables confirmed the importance of TWI in explaining the variability in t_{rise} as it was the most important predictor in the RF runs for the medians of the four rainfall event types. Mean curvature of the upslope contributing and mean TWI of the upslope contributing area were the second or third most important predictor. The correlation between these variables and TWI was high (Tab. 4). Forest percentage and soil depth obtained low ranks and were not relevant for the type 1a and 1b events. The explained variance of the RF regression was $\sim 20\%$ (type 1a events: 24 – 25%, 1b: 9 – 10%, 2a: 10 – 11 % and 2b: 21 – 22%).

When running RFs on t_{rise} for individual events, only half of the runs had an explained variance > 0 (mean: 3.5%; median: 1%; 25%-quantile: -15%; 75%-quantile: 22 %).

Neither the events with a positive, nor the events with a negative explained variance, occurred during a particular season or were characterized by specific rainfall- and antecedent conditions. For the runs with a positive explained variance (1248 runs, ~ 63 events) mean curvature of the upslope contributing area (79%, ~ 54 events), TWI (79%, ~ 52 events), upslope contributing area (44%, ~ 35 events) and mean TWI of the upslope contributing area (39%, ~ 30 events) were the three most important predictors of each RF run (Fig. 7). In contrast, forest percentage and soil depth typically obtained low ranks and were not relevant in explaining the variance for 57% and 71% of all runs respectively. Events for which soil depth and forest percentage of the upslope contributing area were among the three most important ranks (5% or ~ 5 events and 8% or ~ 6 events, respectively) could not be related to specific rainfall characteristics or a specific seasons. There was also no relationship between the number of relevant predictors in an RF regression and rainfall event characteristics.

As expected, the median t_{rise} was related to the median sum of rainfall until the response (P_{rise} ; $r_s = 0.98$) and the mean and maximum rainfall intensity until response ($r_s = 0.92$ and $r_s = 0.96$, respectively). P_{rise} was similar and not significantly different for the four rainfall event types (Tab. 3). The amount of rainfall to initiate a response was expected to depend on the soil water deficit and therefore on the antecedent conditions and indirectly on the topography. The median P_{rise} was indeed correlated to all topographic indices, except for the local curvature (Tab. 4). Similarly to t_{rise} , the median P_{rise} was not correlated with forest percentage of the upslope contributing area or soil depth. The median P_{rise} decreased from > 10 mm to < 1 mm with increasing TWI for sites with a $TWI < 6$; it was constant or decreased slightly for sites with a $TWI \geq 6$ (Fig. 6). Note that these median P_{rise} values only include the events for which there was a water table response. This means that for the 1a-type rainfall events, fewer events are included in the calculation of P_{rise} for sites with a $TWI < 4$ than for sites with a $TWI \geq 4$. For the other event types there was no difference in response frequency between the sites with different TWI values.

3.3.3. Time to peak groundwater level

In general, groundwater peaks lagged the rainfall centroid. For only 3 of the sites, the median t_{peakP} was negative (i.e., the 95 % rise occurred before the centroid of the rainfall; see Fig. 8). Differences in t_{peakP} between the four rainfall event types were small, except for type 1a. The median t_{peakP} under low-intensity/dry antecedent conditions was less than 168 min for half of the sites, while it was considerably shorter (68 – 88 min) for the three other rainfall event types (Tab. 3).

The peak groundwater level is expected to precede peak discharge at the catchment outlet (i.e. negative t_{peakQ}) if groundwater is the main source of runoff. In general, this was the case, as the median t_{peakQ} was less than -20 min for half of the sites (Fig. 8b). However, for 13 of the 51 wells, the median t_{peakQ} was positive (i.e. the 95 % rise in groundwater level occurred after the 95 % rise in discharge). Six out of these 13 sites had a TWI ≤ 4 and three out of the 13 sites a TWI > 6 . Differences in the median t_{peakQ} for the four rainfall event types were small (Tab. 3) and not statistically significant.

The data supported the assumption that the timing of peak groundwater level would not be strongly affected by topography as the r_s between t_{peakP} and TWI, t_{peakQ} and TWI was significant for only 13 and 8 of the 133 events ($\sim 10\%$ and $\sim 8\%$), respectively. These events had predominantly dry antecedent conditions (< 10 mm rainfall during the previous 3 days). The median lagtime to the groundwater peak (median t_{peakP} and median t_{peakQ}) was also not correlated to any of the topographic indices (Tab. 4), except for the type 1a rainfall events for which the median t_{peakP} and the t_{peakQ} were correlated to the upslope contributing area ($r_s = -0.43$ and -0.44), TWI ($r_s = -0.41$ and -0.42), the mean curvature of the upslope contributing area ($r_s = 0.38$ and 0.41) and the mean TWI of the upslope contributing area ($r_s = -0.29$ and -0.31), and for the type 1b rainfall events for which the median t_{peakP} and t_{peakQ} were correlated only to the mean slope of the upslope contributing area ($r_s = 0.30$ and 0.33 , respectively).

The RF runs for median t_{peakP} had an explained variance > 0 only for type 1a events (8 to 9 %). For median t_{peakQ} , most RF runs had an explained variance $< 10\%$. Topographic predictors (TWI, mean TWI of the upslope contributing area or upslope contributing area) and forest percentage of the upslope contributing area were the most important predictors (in order of decreasing importance). Soil depth was either not relevant or obtained low important ranks.

3.3.4. Duration of the peak groundwater level

The duration of the peak groundwater level was expected to be a function of subsurface inputs from the upslope and thus topography. The correlation between t_{dur} and TWI for individual events, was significant for only 13 events ($\sim 10\%$). These events had predominantly moderate rainfall intensities. When all rainfall events were considered together, the median t_{dur} of a monitoring site was correlated to the local slope ($r_s = -0.32$) and the mean TWI of the upslope contributing area ($r_s = 0.29$) (Tab. 4). The median t_{dur} was relatively constant at ca. 120 min for sites with a TWI < 4 , increased up to 180 min with increasing TWI for sites with a TWI between 4 and 6, and remained relatively constant at 180 min for sites with a TWI ≥ 6 , but this correlation was not statistically

significant (Fig. 7a). Median t_{dur} was significantly correlated with local slope, TWI and mean curvature of the upslope contributing area only for the moderate-intensity rainfall events (local slope: type 2a: $r_s = -0.34$ and type 2b: $r_s = -0.35$; TWI: type 2a: $r_s = 0.33$ and type 2b: $r_s = 0.29$, mean curvature of the upslope contributing area: type 2a: $r_s = -0.31$ and type 2b: $r_s = -0.29$). None of the RF runs for median t_{dur} had a positive explained variance.

3.3.5. Duration of the groundwater levels recession

The groundwater recession was expected to be slower for sites that receive a more persistent water input from their upslope contributing area and sites that are poorly drained. The median t_{rec} was indeed correlated to local slope ($r_s = -0.39$), TWI ($r_s = 0.38$), mean curvature of the upslope contributing area ($r_s = -0.37$) and the size of the upslope contributing area ($r_s = 0.32$) but not to any of the other indices (Tab. 4). The median t_{rec} increased from ca. 6 hours to 14 hours with increasing TWI for sites with a $TWI < 6$, but the variability was high (Fig. 9b). The median t_{rec} was relatively constant for sites with $TWI \geq 6$ (14 hours). The median t_{rec} was longer for events with dry antecedent conditions than for events with wet antecedent conditions but the differences in median t_{rec} and s_{rec} for the different rainfall event types were not significant, except for event type 1a.

There was no significant correlation between t_{rec} and TWI or between s_{rec} and TWI for 94% and 74% of the events. The 8 events with a significant correlation between t_{rec} and TWI were not characterized by distinct rainfall and antecedent conditions. The events with a significant correlation between s_{rec} and TWI were predominantly characterized by wet antecedent conditions (event types 1b, 2b) but occurred throughout the years. The RF runs for median t_{rec} had a positive explained variance only for the type 2b events (< 7 %). None of the RF runs for the median s_{rec} had a positive explained variance.

4. DISCUSSION

4.1. Influence of topography on groundwater response timing

The results show that in the study catchment the timing of the onset of the groundwater rise and the recession are strongly related to topography. The more the flow pathways in the upslope contributing area are convergent (as described by the mean curvature of the upslope contributing area) and the larger the subsurface water inputs from upslope (as described by the upslope contributing area), the quicker the groundwater levels respond and the slower they decline. Similarly, the smaller the hydraulic gradient (described by the local slope) and the larger the soil wetness (as described by the TWI), the quicker the groundwater response and the slower the recession.

The strong correlation between the median P_{rise} and the topographic characteristics (Tab. 4 and Fig. 6) allows the point measurements to be extrapolated to the catchment scale and thus to identify the parts of a catchment that are likely to respond as a function of

cumulative event precipitation. These type of maps could be used to determine when individual parts of the catchment respond to rainfall and become hydrologically connected to the stream. According to the functional relation between the median P_{rise} and TWI (the LOWESS curve in Fig. 6), wet sites close to the stream and in isolated depressions on hillslopes start to respond on average after only 1 mm of cumulative rainfall (44 % of total catchment area) (Fig. 10), while a groundwater response occurs in 87 % of the catchment after 5 mm of cumulative rainfall. However the large IQR for each site (Fig. 6) suggests that this overall pattern is different for individual rainfall events and, even though we could not find a significant correlation between forest percentage of the upslope contributing area and t_{rise} and P_{rise} , this spatial pattern is also influenced by interception losses. This map also does not account for events that did not cause a response at all. One could expect that this is more likely for sites with a low TWI but the response frequencies were generally high and did not depend on TWI, except for the type 1a rainfall events.

The results suggest that dry and intermediate sites (located mainly on ridges and backslopes) are the zones with the highest soil water storage dynamics as they require more precipitation to satisfy the storage deficit. Rinderer et al (2014) showed for the same study catchment that backslopes with a TWI between 4-6, a local slope between 30-50 % and an upslope contributing area between 200-600 m² were the zones of highest variability in median groundwater level. This study shows that the water level response on backslopes was delayed, while wet sites in footslope locations responded very quickly. This is particularly relevant for identifying the parts of the catchment, where hydrological connectivity to the stream network is quickly established and the areas that can contribute to the rapid streamflow response. The delayed establishment of hydrologic connectivity in the most dynamic groundwater zones of the catchment could then be a plausible explanation for the flashy peak flows, that are typical for the streams in the Alptal region (Cosandey & de Oliveira 1996; Hegg et al. 2006).

Previous studies have not explicitly analyzed the topographic controls on the time to groundwater rise or the duration of the recession but agree with our results as they showed that groundwater wells near the stream or in footslope locations were well correlated with streamflow or even preceded it, while the water levels in upslope wells were not correlated to streamflow and the response lagged behind the steamflow response (Seibert et al. 2003; Haught & van Meerveld 2011). We can assume that the near-stream locations had a large upslope contributing area, low slope gradient and high TWI and that connectivity to the stream was therefore quickly established (Jencso et al. 2009). However, on other hillslopes with permeable soils, groundwater wells responded earlier in uphill locations than in footslopes and the onset of the groundwater response was more dependent on the spatial distribution of soil depth and the bedrock topography than surface topography (Penna et al. 2014). In a RF analysis to explain the variability of the groundwater response frequency for hillslopes in Southern Germany, soil properties obtained the highest ranks. Topography also obtained high ranks and was more important than vegetation characteristics (Bachmair et al. 2012).

Our data did not show a significant correlation between t_{peakP} or t_{peakQ} and surface topography when all events were considered together. Groundwater peaks generally preceded peak discharge at the catchment outlet but the median t_{peakQ} was shorter than -

20 min. For 65 % of all rainfall events, the catchment median groundwater peak occurred earlier than peak streamflow at the catchment outlet. However the large IQR in Fig. 8 also shows that groundwater peaks frequently lagged the streamflow peak by several hours. This is in agreement with other studies that have shown, based on end-member mixing analysis that hillslopes mainly contribute to streamflow during the recession (McGlynn & McDonnell 2003; Burns et al. 2001).

Previous studies have not investigated the correlation between peak lag times and topographic indices explicitly, but have reported that peak-to-peak lag times vary with soil depth and distance from the stream and therefore with topographic position (uphill-, downhill locations) (Seibert et al. 2003; Haught & van Meerveld 2011; Rodhe & Seibert 2011; Penna et al. 2014). Assuming a different upslope contributing area and TWI for uphill and downhill locations, these findings would not agree with our results. For a more direct comparison we also analyzed soil depth (i.e., well depth, as the wells were installed down to depth of refusal) and distance from the stream but they were also not correlated with t_{peakP} and t_{peakQ} . Bachmair et al. (2012) reported a high spatial variability of peak-to-peak lagtimes, especially during the wet seasons. This agrees with the observations in the study catchment, which is wet throughout the year.

The duration of the groundwater peak was more dominated by local drainage than by the subsurface contribution from the upslope. A possible explanation can be that the upslope contributing area was only partly hydrologically connected, subsurface flow volumes varied spatially and were not related to surface topography, or that drainage affected t_{dur} more than the variability of the subsurface input. The duration of the recession, on the other hand, was related to both the upslope inputs (represented by the contributing area) and the drainage (represented by the local slope).

We expect our findings to be transferable to other humid temperate mountain catchments with low permeability soils and shallow groundwater tables as the topographic characteristics describe the physical properties that dominate groundwater flow in these catchments. The correlations between the groundwater response timing characteristics and topographic characteristics became clear when reducing the natural variability by computing the median response timing for the large data set. The response time characteristics showed considerable variability (see IQR in Fig. 5 to Fig. 9) and the correlation between the response timing characteristics and topography was often not significant for individual events, i.e. for 31 % of the events we did not find a significant correlation between TWI and t_{rise} . The response time characteristics were likely also influenced by natural heterogeneity in soil properties and vegetation, even though soil depth and forest percentage of the upslope contributing area were not correlated to the timing characteristics in this study, nor obtained important ranks in the RF regression analysis,

4.2. Influence of rainfall characteristics and antecedent conditions on groundwater response timing

Previous studies have seldom reported actual lag times and more frequently reported the number of wells that were activated during events. The groundwater response frequency

in the study catchment was higher than in other catchments (Bachmair et al. 2012; Smith et al. 2014; Detty & McGuire 2010). The response frequency was more strongly influenced by rainfall intensity than antecedent precipitation. These results are in agreement with previous studies, as they generally reported a high correlation between the percentage of well activation and total event precipitation, an intermediate correlation with rainfall intensity and a weak or no correlation with antecedent wetness conditions (Bachmair et al. 2012; Penna et al. 2014). In our study catchment topography influenced the response frequency only for low-intensity rainfall events with dry antecedent conditions.

The groundwater response timing was mainly dominated by static controls (topography). The dynamic characteristics (rainfall intensity but not antecedent conditions) only had a minor effect on the functional relation between the median t_{rise} and TWI. The amount of rainfall to initiate a groundwater responses (P_{rise}) depended on the topography but was similar for individual events. P_{rise} was not significantly different for the four rainfall event types (Tab. 3). For dry and intermediate sites ($TWI < 6$), the storage had to be filled before the groundwater level would respond, while wet sites ($TWI \geq 6$) seemed to have persistently low storage deficits and therefore responded quickly, regardless of rainfall intensity and antecedent precipitation. Because the response for the dry sites was mainly related to the storage deficit, the time to response was slower for the low intensity events than for the high intensity events.

The timing of the groundwater peak (t_{peakP} and t_{peakQ}) did not depend on topographic position, but likely more on the rainfall dynamics. The peak lag times were related to topography for only a few events with dry antecedent conditions. The median lagtimes to rainfall were short and similar for the four rainfall event types (except type 1a), suggesting that the rainfall input signal propagated quickly to the groundwater regardless of rainfall intensity and event duration. Only for type 1a events did specific differences in storage deficit affect the timing of the peak groundwater levels.

The duration of the groundwater recession was correlated to TWI for only a few events. These events were not characterized by particular antecedent wetness conditions or rainfall intensities. However, topographic indices were significantly correlated to the median t_{rec} . The groundwater recession was longer and more variable for dry than wet antecedent conditions. This could partly be an artifact caused by differences in the groundwater amplitude between dry and wet conditions, as the antecedent groundwater levels were lower during dry conditions and the rise and decline in water level was larger. Drainage from deeper soil horizons may also be slower due to the lower hydraulic conductivity deeper in the soil profile. However, the median slope of the recession (s_{rec}) was not different for the four rainfall event types.

5. CONCLUSIONS

The objective of this study was to assess the effects of topography on the groundwater response timing in a 20 ha pre-alpine catchment with low permeability soils and how it is affected by rainfall and antecedent wetness conditions. The large dataset allowed us to

reveal strong correlations between the groundwater response timing and topography. Results of a rank correlation analysis and multivariate regression tree analysis based on data from 51 groundwater monitoring sites and 133 rainfall events suggest that topography is a good predictor for the time to groundwater rise and the duration of the recession but not for the timing of the peak groundwater level. Rainfall is only a secondary control on the response time.

Topography controls the time to groundwater rise by influencing subsurface inputs from upslope and convergence of shallow flow pathways, soil drainage and associated difference in soil water deficits. Topography also controls the groundwater recession by affecting the balance between local drainage and subsurface inputs from upslope areas. The rainfall threshold for groundwater initiation was also strongly dependent on topography. The relationships between topographic characteristics and the cumulative rainfall (P_{rise}) or the time to rise (t_{rise}) could allow prediction of the spatial patterns of expected groundwater response zones. This would enable extrapolation of point measurements to the catchment scale and assessment of the changes of runoff source areas and hydrological connectivity during rainfall events.

The response timing was affected by second order controls. Rainfall intensity influenced the time to rise by determining the time needed to satisfy the soil moisture deficits. In contrast, the antecedent rainfall conditions played only a minor role for the groundwater response timing in this wet study catchment, where groundwater levels are generally high throughout the year.

The topographic indices were a good predictor of the groundwater response timing in this study catchment, while previous studies in catchments with more permeable soils suggested that soil properties and bedrock topography were more important. From this we conclude that surface topography might play a more important role in determining the variability in groundwater response timing in catchments with low permeability soils and predominantly shallow groundwater tables than in catchments with more transmissive soils (Tromp-van Meerveld & McDonnell 2006; Bachmair et al. 2012; Penna et al. 2014). This would agree with results of Hutchinson and Moore (2000) that hydraulic gradients reflect the surface topography more during periods of high water levels and flow than during periods of low water levels.

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7. REFERENCES

- Anderson, A.E., Weiler, M., Alila, Y. & Hudson, R.O., 2010. Piezometric response in zones of a watershed with lateral preferential flow as a first-order control on subsurface flow. *Hydrological Processes*, 24(16), pp.2237–2247.
- Anderson, M.G. & Burt, T.P., 1978. The role of topography in controlling throughflow generation. *Earth Surface Processes and Landforms*, 3, pp.331–334.
- Bachmair, S. & Weiler, M., 2012. Hillslope characteristics as controls of subsurface flow variability. *Hydrology and Earth System Sciences*, 16(10), pp.3699–3715.
- Bachmair, S., Weiler, M. & Troch, P. a., 2012. Intercomparing hillslope hydrological dynamics: Spatio-temporal variability and vegetation cover effects. *Water Resources Research*, 48(5), p.W05537.
- Barling, R.D., Corporation, W., Moore, I.D. & Grayson, B., 1994. A quasi dynamic wetness index for characterizing the spatial distribution of zones of surface saturation and soil water content. *Water Resources*, 30(4), pp.1029–1044.
- Beven, K.J. & Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin*, 24(1), pp.43–69.
- Breiman, L., 2001. Random Forests. *Machine Learning*, 45, pp.5–32.
- Burns, D. a., McDonnell, J.J., Hooper, R.P., Peters, N.E., Freer, J.E., Kendall, C. & Beven, K., 2001. Quantifying contributions to storm runoff through end-member mixing analysis and hydrologic measurements at the Panola Mountain Research Watershed (Georgia, USA). *Hydrological Processes*, 15(10), pp.1903–1924.
- Burt, T.P. & Butcher, D.P., 1985. Topographic controls of soil moisture distributions. *Journal of Soil Science*, 36(1978), pp.469–486.
- Conrad, O., 2007. *Entwurf, Funktionsumfang, und Anwendung eines Systems für Automatisierte Geowissenschaftliche Analysen*. University of Göttingen.
- Cosandey, C. & de Oliveira, M., 1996. Surfaces saturées, surfaces contributives: localisation et extension dans l'espace du bassin versant. *Hydrological Sciences Journal*, 41(5), pp.751–761.
- Detty, J.M. & McGuire, K.J., 2010. Topographic controls on shallow groundwater dynamics: implications of hydrologic connectivity between hillslopes and riparian zones in a till mantled catchment. *Hydrological Processes*, 24(16), pp.2222–2236.
- Development Core Team, R., 2005. *R: A language and environment for statistical computing*, Vienna.
- Dhakal, A.S. & Sullivan, K., 2014. Shallow groundwater response to rainfall on a forested headwater catchment in northern coastal California: implications of topography, rainfall, and throughfall intensities on peak pressure head generation. *Hydrological Processes*, 28, pp.446–463.
- Evans, S., 1980. An integrated system of terrain analysis and slope mapping. *Zeitschrift für Geomorphologie*, Supl. Bd.(36), pp.274–294.

- Fannin, R.J., Jaakkola, J., Wilkinson, J.M.T. & Hetherington, E.D., 2000. Hydrologic response of soils to precipitation at Carnation Creek, British Columbia, Canada. *Water Resources Research*, 36(6), pp.1481–1494.
- Feyen, H., Wunderli, H., Wydler, H. & Papritz, A., 1999. A tracer experiment to study flow paths of water in a forest soil. *Journal of Hydrology*, 225(3-4), pp.155–167.
- Hagedorn, F., Schleppi, P., Bucher, J. & Flühler, H., 2001. Retention and leaching of elevated N deposition in a forest ecosystem with Gleysols. *Water, Air, and Soil Pollution*, 129, pp.119–142.
- Hagedorn, F., Schleppi, P., Waldner, P. & Flühler, H., 2000. Export of dissolved organic carbon and nitrogen from Gleysol dominated catchments—the significance of water flow paths. *Biogeochemistry*, 50, pp.137–161.
- Hammermeister, D.P., Kling, G.F. & Vomocil, J.A., 1982. Perched Water Tables on Hillsides in Western Oregon: I. Some Factors Affecting Their Development and Longevity. *Soil Science Society of America Journal*, 46(4), pp.811–818.
- Haught, D.R.W. & van Meerveld, H.J., 2011. Spatial variation in transient water table responses: differences between an upper and lower hillslope zone. *Hydrological Processes*, 25(25), pp.3866–3877.
- Hegg, C., McArdeall, B.W. & Badoux, A., 2006. One hundred years of mountain hydrology in Switzerland by the WSL. *Hydrological Processes*, 20(2), pp.371–376.
- Hutchinson, D.G. & Moore, R.D., 2000. Throughflow variability on a forested hillslope underlain by compacted glacial till. , (May 1999), pp.640–655.
- Jencso, K.G., McGlynn, B.L., Gooseff, M.N., Wondzell, S.M., Bencala, K.E. & Marshall, L.A., 2009. Hydrologic connectivity between landscapes and streams: Transferring reach-and plot-scale understanding to the catchment scale. *Water Resources Research*, 45, p.-.
- Lana-Renault, N., Regüés, D., Serrano, P. & Latron, J., 2014. Spatial and temporal variability of groundwater dynamics in a sub-Mediterranean mountain catchment. *Hydrological Processes*, 28(8), pp.3288–3299.
- Liaw, a & Wiener, M., 2002. Classification and Regression by randomForest. *R news*, 2, pp.18–22.
- Lowery, B., Kling, G. & Vomocil, J., 1982. Overland Flow from Sloping Land: Effects of Perched Water Tables and Subsurface Drains. *Soil Science Society of America Journal*, 46, pp.93–99.
- McDonnell, J.J., 1990. A Rationale for Old Water Discharge through Macropores in a Steep, Humid Catchment. *Water Resources Research*, 26(11), pp.2821–2832.
- McDonnell, J.J., Sivapalan, M., Vache, K., Dunn, S., Grant, G., Haggerty, R., Hinz, C., Hooper, R., Kirchner, J., Roderick, M.L., Selker, J. & Weiler, M., 2007. Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology. *Water Resources Research*, 43(7), pp.1–6.
- McGlynn, B.L. & McDonnell, J.J., 2003. Quantifying the relative contributions of riparian and hillslope zones to catchment runoff. *Water Resources Research*, 39(11), pp.1310–1320.

- Mohn, J., Schürmann, A. & Hagedorn, F., 2000. Increased rates of denitrification in nitrogen-treated forest soils. *Forest Ecology and Management*, 137, pp.113–119.
- Moore, R.D. & Thompson, J.C., 1996. Are Water Table Variations in a Shallow Forest Soil Consistent with the TOPMODEL Concept? *Water Resources Research*, 32(3), pp.663–669.
- Penna, D., Mantese, N., Hopp, L., Borga, M. & Dalla Fontana, G., 2014. Spatio-temporal variability of piezometric response on two steep alpine hillslopes. *Hydrological Processes*, 29(2), pp.198–211.
- Rinderer, M., van Meerveld, I. & Seibert, J., 2014. Topographic controls on shallow groundwater levels in a steep, prealpine catchment: When are the TWI assumptions valid? *Water Resources Research*, 50(7), pp.6067–6080.
- Rodhe, A. & Seibert, J., 2011. Groundwater dynamics in a till hillslope: flow directions, gradients and delay. *Hydrological Processes*, 25(12), pp.1899–1909.
- Scanlon, T.M., Raffensperger, J.P., Hornberger, G.M. & Clapp, R.B., 2000. Shallow subsurface stream flow in a forested headwater catchment: Observations and modeling using a modified TOPMODEL. *Water Resources Research*, 36(9), pp.2575–2586.
- Schleppi, P., Müller, N., Feyen, H., Papritz, A., Bucher, J.B. & Flühler, H., 1998. Nitrogen budgets of two small experimental forested catchments at Alptal, Switzerland. *Forest Ecology and Management*, 101, pp.177–185.
- Seibert, J., Bishop, K. & Nyberg, L., 1997. A test of TOPMODEL's ability to predict spatially distributed groundwater levels. *Hydrological Processes*, 11, pp.1131–1144.
- Seibert, J., Bishop, K., Rodhe, A. & McDonnell, J.J., 2003. Groundwater dynamics along a hillslope: A test of the steady state hypothesis. *Water Resources Research*, 39(1), pp.1014–1023.
- Seibert, J. & McGlynn, B.L., 2007. A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models. *Water Resources Research*, 43(4), p.-.
- Sklash, M. & Farvolden, R., 1979. The role of groundwater in storm runoff. *Journal of Hydrology*, 43, pp.45 – 65.
- Smith, R.S., Moore, R.D., Weiler, M. & Jost, G., 2014. Spatial controls on groundwater response dynamics in a snowmelt-dominated montane catchment. *Hydrology and Earth System Sciences*, 18(5), pp.1835–1856.
- Strobl, C., Malley, J. & Tutz, G., 2009. An Introduction to Recursive Partitioning: Rationale, Application and Characteristics of Classification and Regression Trees, Bagging and Random Forests. *Psychological Methods*, 14, pp.323–348.
- Tarboton, G.D., 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. *Water Resources*, 33(2), pp.309–319.
- Travis, M.R., Iverson, W.D., Gary, H. & Johnson, C.G., 1975. *VIEWIT: computation of seen area, slope and aspect for land-use planning PSW 11*, Berkeley, California U.S.A.: USDA - Forest Service.

Troch, P.A., Mancini, M., Paniconi, C. & Wood, E.F., 1993. Evaluation of a Distributed Catchment Scale Water Balance Model. *Water Resources*, 29(6), pp.1805–1817.

Tromp-van Meerveld, H.J. & McDonnell, J.J., 2006. Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. *Water Resources Research*, 42(2), pp.1–11.

Weiler, M., McDonnell, J.J., Tromp-Van Meerveld, I. & Uchida, T., 2005. Subsurface Stormflow. In G. M. Anderson & J. J. McDonnell, eds. *Encyclopedia of Hydrological Sciences*. pp. 1719–1732.

Wilson, G.V., Jardine, P.M., Luxmoore, R.J. & Jones, J.R., 1990. Hydrology of a forested hillslope during storm events. *Geoderma*, 46(1-3), pp.119–138.

Tab. 1: The main characteristics of the four rainfall event types: Different superscript letters indicate pairs that are significantly different based on a pairwise Mann-Whitney test and Bonferroni adjusted p-values.

	Rainfall Event Type				
	1a	1b	2a	2b	all
Intensity	low	low	moderate	moderate	-
Antecedent wetness	dry	wet	dry	wet	-
Number of events	30	27	33	43	133
Median average intensity [mm/h]	1.1 ^a	1.2 ^a	3.3 ^b	2.9 ^b	2.0
Median 3 day antecedent rainfall [mm]	2.1 ^a	27.9 ^b	1.7 ^a	22.4 ^b	11.1
Median maximum intensity [mm/10min]	1 ^a	1.4 ^a	2.5 ^b	2.8 ^b	1.8
Median event sum [mm]	11.3 ^a	14.5 ^{ab}	18 ^{bc}	20.6 ^{ac}	17.4
Median time to rainfall centroid [min]	320 ^a	360 ^a	130 ^b	210 ^{ab}	240
Median event duration [min]	670 ^a	720 ^a	330 ^b	480 ^{ab}	550

Tab. 2: Definition of the timing characteristics used in this study. See Fig. 2 for a schematic overview of the timing parameters.

Parameter	Definition
t_{rise}	Timelag between the start of rainfall and the first response of the groundwater level [min]
t_{peakP}	Timelag between the centroid of rainfall and the time of the 95 % of the maximum groundwater level rise [min]
t_{peakQ}	Timelag between the time of the 95 % of the maximum rise in discharge at the catchment outlet and the time of the 95 % of the maximum rise of the groundwater level [min]
t_{dur}	Time between the time of the 95 % of the maximum groundwater level rise on the rising limb of the groundwater hydrograph and the corresponding point on the falling limb (called 95 % recession) [min]
t_{rec}	Time between the time of the 95 % of the maximum groundwater level rise and the time of the 20 % of the maximum groundwater level rise on the falling limb of the groundwater hydrograph [min]
s_{rec}	Mean slope of the groundwater hydrograph between 95 % of recession and 20 % of recession [cm/min]
P_{rise}	Sum of rainfall before the start of the groundwater level response [mm]

Tab. 3: Median and Inter Quartile Range (IQR) of the median groundwater timing characteristics for each well for the different rainfall event types. Different superscript letters indicate pairs that are significantly different based on a pairwise Mann-Whitney test and Bonferroni adjusted p-values.

		Rainfall Event Type				
		1a	1b	2a	2b	all
Intensity	-	low	low	moderate	moderate	-
Antecedent Wetness	-	dry	wet	dry	wet	-
Median t_{rise} [min]	median	50 ^{ab}	78 ^a	20 ^b	30 ^b	35
	IQR	(8 - 162)	(24 - 174)	(0 - 70)	(5 - 78)	(5 - 105)
Median t_{peakP} [min]	median	164 ^a	88 ^{ab}	80 ^b	58 ^b	75
	IQR	(76 - 273)	(36 - 169)	(25 - 143)	(34 - 101)	(41 - 129)
Median t_{peakQ} [min]	median	-20 ^a	-13 ^a	-25 ^a	-15 ^a	-20
	IQR	(-65 - 95)	(-42 - 59)	(-39 - 28)	(-38 - 25)	(-43 - 18)
Median t_{dur} [min]	median	222 ^a	118 ^b	198 ^{ab}	135 ^b	145
	IQR	(125 - 293)	(65 - 199)	(80 - 300)	(73 - 190)	(88 - 242)
Median t_{rec} [min]	median	1410 ^a	449 ^b	905 ^a	602 ^b	750
	IQR	(686 - 2078)	(368 - 562)	(483 - 1650)	(360 - 749)	(458 - 920)
Median s_{rec} [cm/min]	median	-0.005 ^a	-0.011 ^a	-0.01 ^a	-0.011 ^a	-0.009
	IQR	(-0.013 - -0.003)	(-0.021 - -0.006)	(-0.034 - -0.006)	(-0.025 - -0.006)	(-0.023 - -0.005)
Median P_{rise} [mm]	median	1.2 ^a	1.2 ^a	1.2 ^a	1.3 ^a	1.1
	IQR	(0.4 - 4.0)	(0.6 - 3.1)	(0.5 - 5.1)	(0.5 - 4.4)	(0.5 - 4.1)

Tab. 4: Spearman Rank correlation matrix between the median response characteristics and the topographic site characteristics. For a definition of the response timing characteristics see Table 2. Upper right triangle: r_s values, lower left triangle: p-values. Statistically significant r_s values are shown in bold font.

	Local slope	Mean slope of the upslope contributing area	Local curvature	Mean curvature of the upslope contributing area	Upslope contributing area	Topographic Wetness Index (TWI)	Mean TWI of the upslope contributing area	Forest percentage of the upslope contributing area	Soil depth	median t_{rise}	median t_{peakp}	median t_{peakQ}	median t_{dur}	median t_{rec}	median P_{rise}
Local slope															
Mean slope of the upslope contributing area		0.61	0.27	0.61	-0.44	-0.64	-0.43	0.07	-0.44	0.64	-0.05	0.03	-0.32	-0.39	0.67
Local curvature	<0.001		0.07	0.22	-0.07	-0.24	-0.31	0.38	-0.23	0.29	0.06	0.22	-0.05	-0.13	0.36
Mean curvature of the upslope contributing area	0.05	0.64		0.45	-0.48	-0.51	-0.10	-0.13	0.09	0.28	0.02	-0.13	0.06	-0.14	0.27
Upslope contributing area	<0.001	0.11	<0.01		-0.94	-0.97	-0.80	0.15	-0.25	0.82	0.09	0.06	-0.26	-0.37	0.81
Topographic Wetness Index (TWI)	<0.01	0.60	<0.001	<0.001		0.96	0.73	-0.15	0.16	-0.74	-0.13	-0.07	0.23	0.32	-0.72
Mean TWI of the upslope contributing area	<0.001	0.10	<0.001	<0.001	<0.001		0.73	-0.13	0.24	-0.81	-0.09	-0.05	0.27	0.38	-0.81
Forest percentage of the upslope contributing area	<0.01	0.03	0.50	<0.001	<0.001	<0.001		-0.39	0.21	-0.66	-0.19	-0.29	0.29	0.22	-0.65
Soil depth	0.65	<0.01	0.36	0.29	0.29	0.36	<0.01		-0.2	0.26	0.05	0.13	-0.09	0.23	0.24
median t_{rise}	<0.01	0.10	0.55	0.08	0.26	0.09	0.15	0.16		-0.27	0.17	0.14	0.19	0.22	-0.23
median t_{peakp}	<0.001	0.04	0.04	<0.001	<0.001	<0.001	<0.001	0.07	0.06		0.06	0.06	-0.40	-0.35	0.98
median t_{peakQ}	0.73	0.66	0.90	0.54	0.37	0.55	0.18	0.73	0.24	0.68		0.82	0.23	0.05	0.10
median t_{dur}	0.85	0.11	0.38	0.67	0.64	0.75	0.04	0.35	0.31	0.69	<0.001		0.09	-0.05	0.11
median t_{rec}	0.02	0.72	0.68	0.07	0.10	0.05	0.04	0.54	0.17	<0.01	0.10	0.52		0.50	-0.35
median P_{rise}	<0.01	0.36	0.34	<0.01	0.02	<0.01	0.12	0.11	0.13	0.01	0.71	0.75	<0.001		-0.33
	<0.001	<0.01	0.06	<0.001	<0.001	<0.001	<0.001	0.10	0.10	<0.001	0.50	0.45	0.01	0.02	

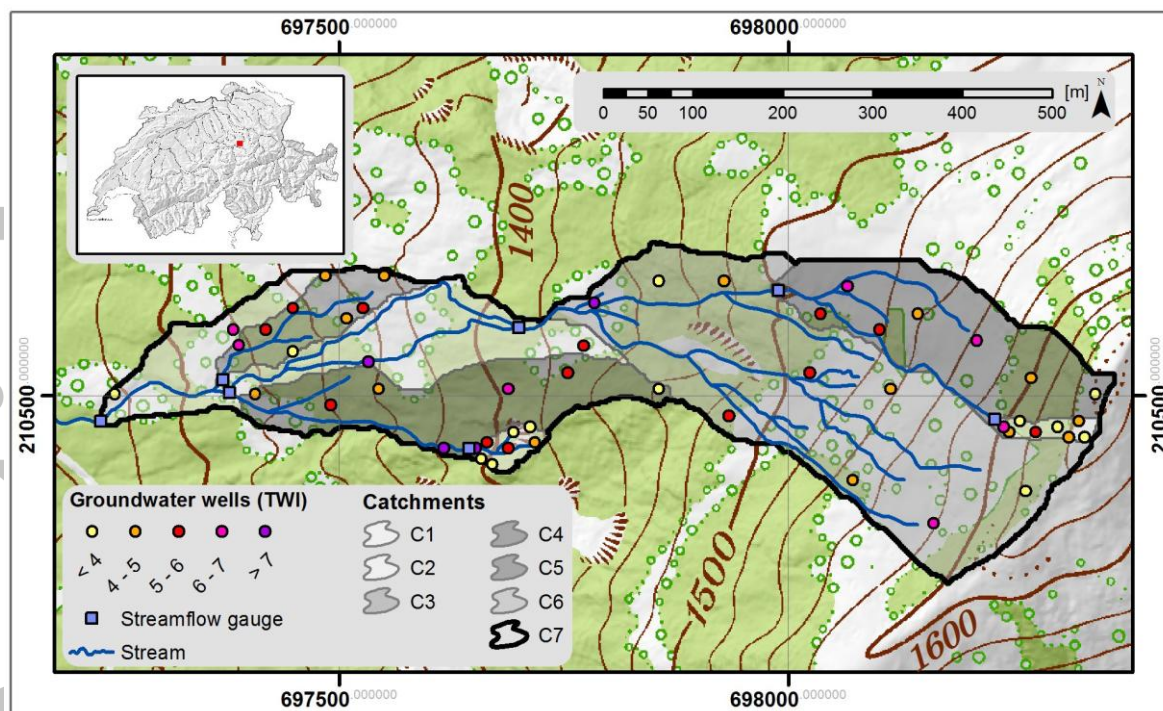


Fig. 1: Map of the study catchment showing the seven nested sub-catchments and the location of the 51 spatially distributed groundwater wells. Groundwater wells are color-coded according to the Topographic Wetness Index (TWI). Inset: location of the catchment in Switzerland. (Background-topographic map: Swisstopo, 123456789).

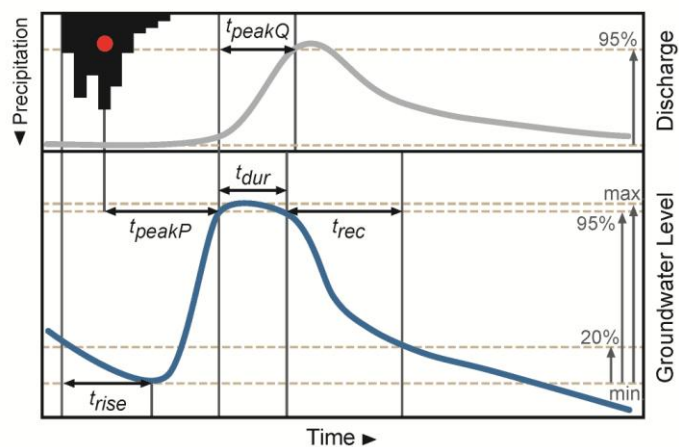


Fig. 2: Schematic groundwater and streamflow hydrograph and timing characteristics as described in table 2. The red dot represents the centroid of rainfall.

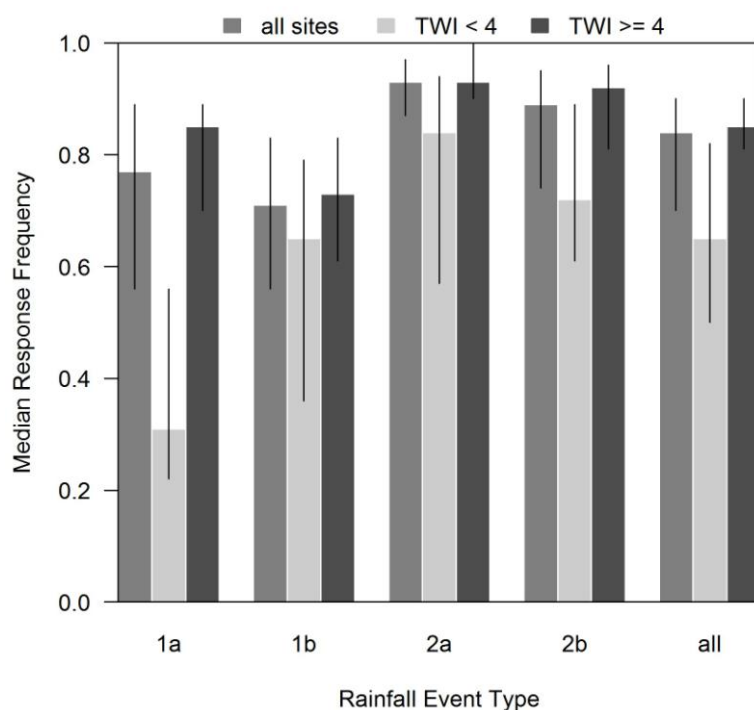


Fig. 3: Median relative frequency and Inter Quartile Range (IQR) of groundwater responses for different rainfall event types for all sites, for sites with a TWI < 4 and for sites with a TWI \geq 4. See table 1 for a description of the rainfall event types.

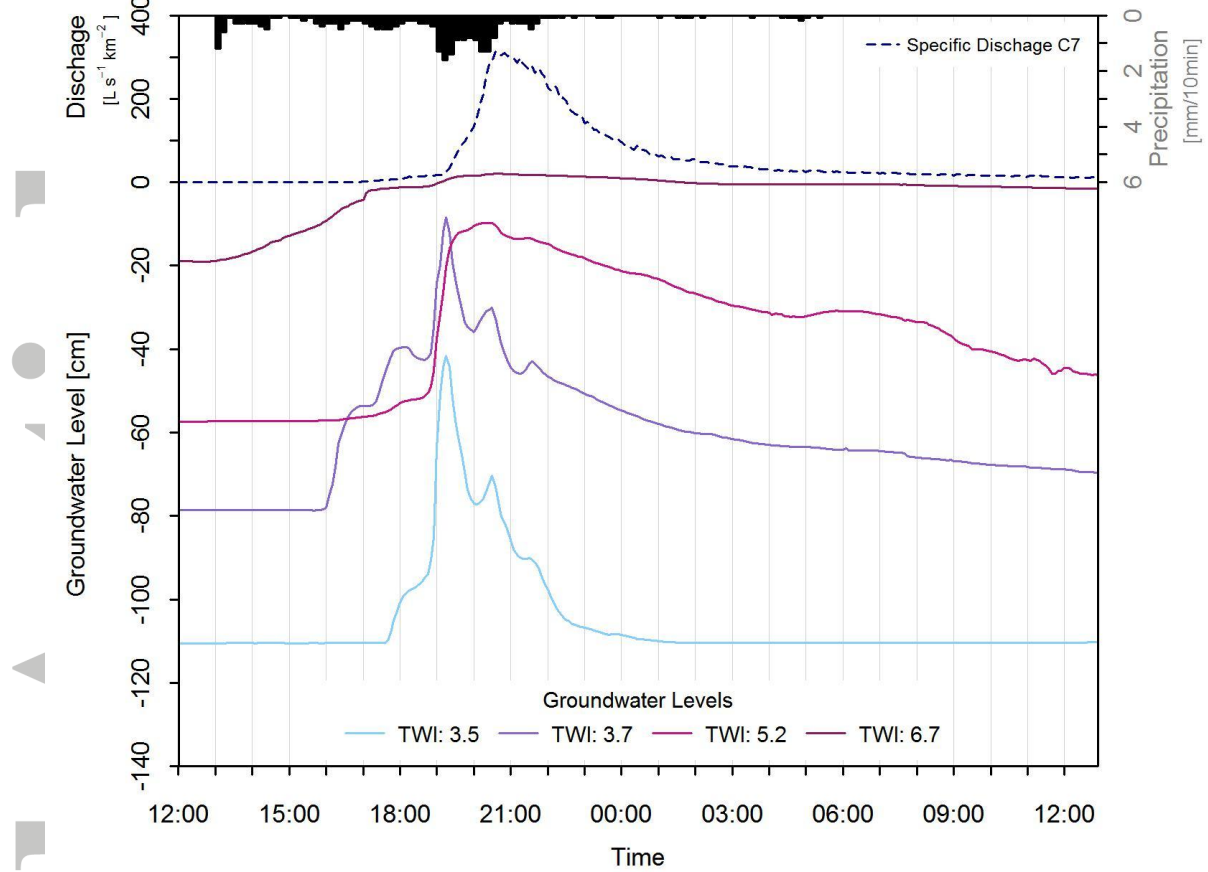


Fig. 4: Groundwater level responses of selected monitoring sites, specific discharge at the catchment outlet (C7) and precipitation for a typical rainfall event (31 May to 1 June 2011). Groundwater monitoring sites with a low TWI are shown with dotted lines, sites with an intermediate TWI with dashed lines, sites with a high TWI with long dashed lines and sites with a very high TWI with dash dotted lines. Specific discharge is shown in the upper panel with a solid line.

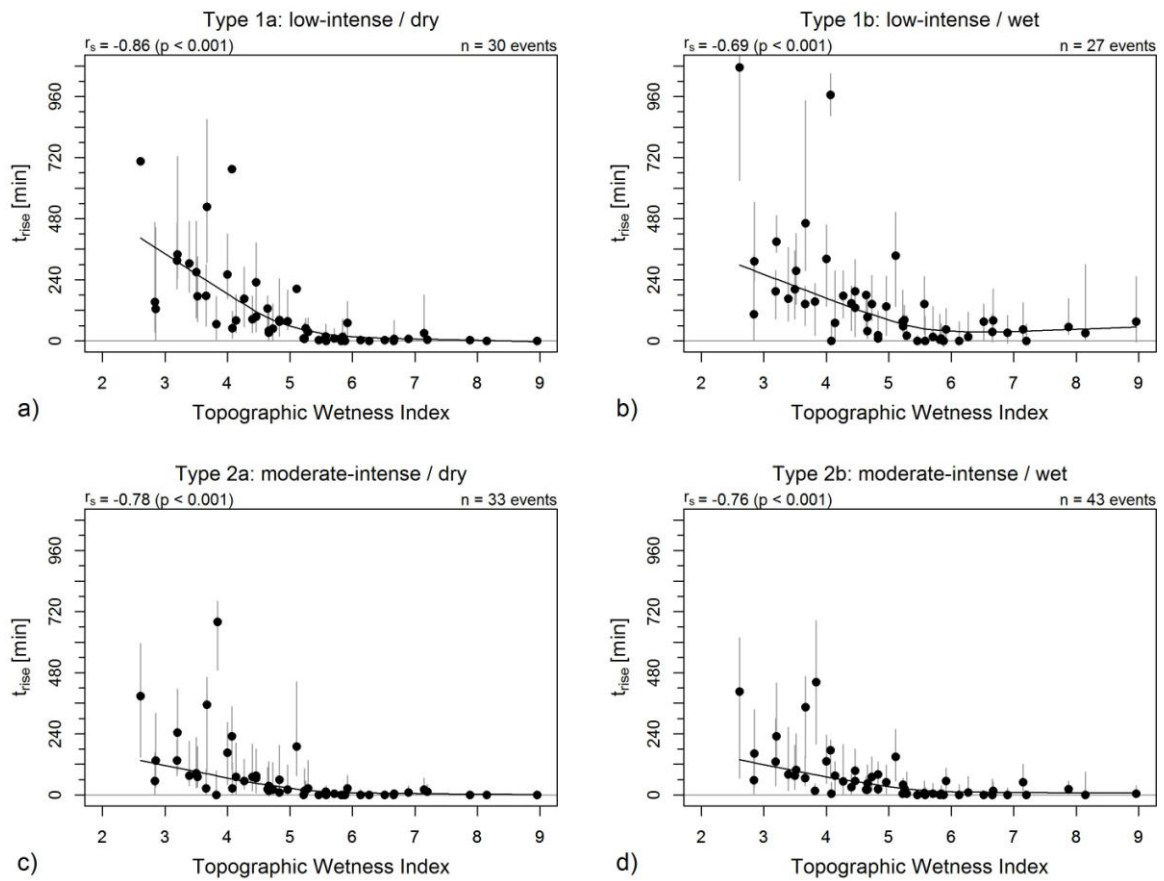


Fig. 5: Time to rise (t_{rise}) as a function of Topographic Wetness Index for the four rainfall event types. Grey bar: inter quartile range, dot: median for each site, black line: LOWESS curves fitted to the median values, r_s : Spearman Rank Correlation Coefficient and associated p-value.

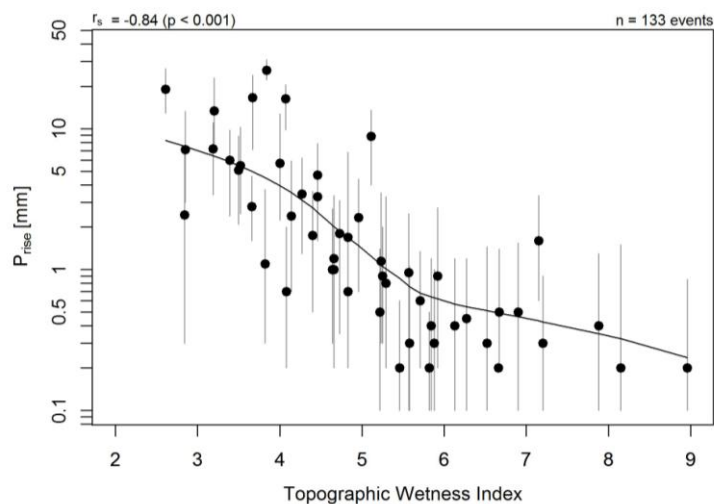


Fig. 6: Sum of rainfall until the start of the groundwater level response (P_{rise}) as a function of Topographic Wetness Index for all 133 rainfall events and all sites. Grey bar: inter quartile range, dot: median for each site, black line: LOWESS curves fitted to the median values, r_s : Spearman Rank Correlation Coefficient and associated p-value.

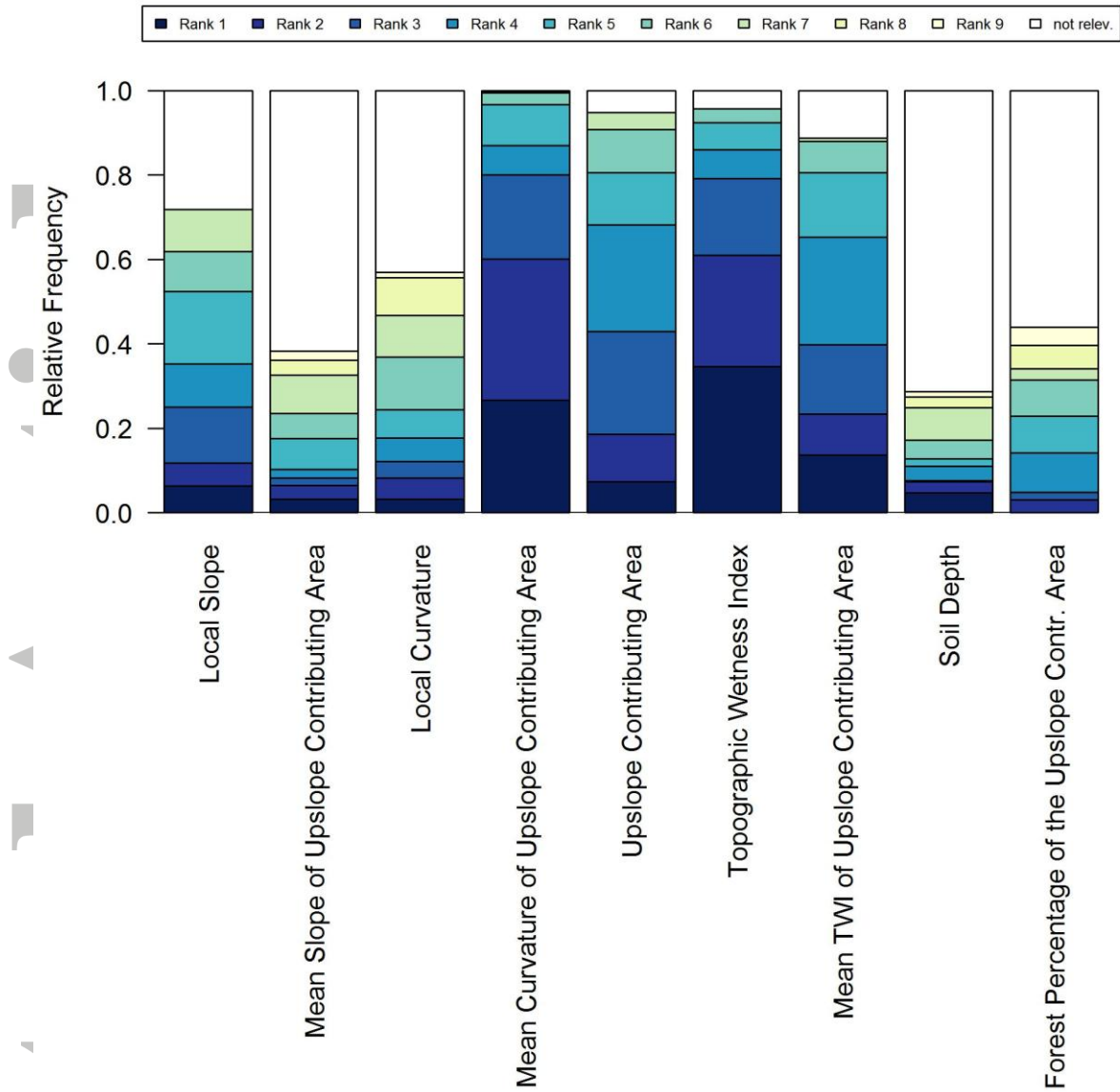


Fig. 7: Relative frequency of the ranks of the site characteristics in explaining the spatial variability in t_{rise} for the random forest (RF) analysis considering the individual rainfall events. Dark colors indicate a rank of high importance, light colors a rank of low importance. White identifies the fraction of runs for which a predictor was not considered relevant. For example: Topographic Wetness Index was the most important predictor in 35% of all RF runs (dark blue bar), second most important predictor in 26 % of all runs and not significant in only 4 % of all RF runs (topmost white bar). Note that in RF regression correlated predictors can be incorporated without biasing the result (e.g. curvature of the upslope contributing area and topographic wetness index are highly correlated ($r_s = -0.97$) but both are strong predictors).

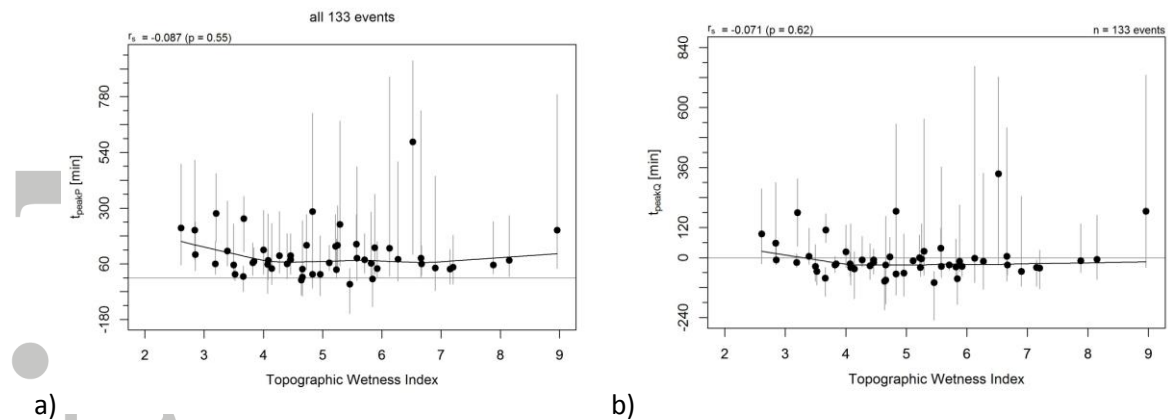


Fig. 8: Time lag between the centroid of rainfall and the time of the 95 % of the maximum rise in groundwater level (t_{peakP}) (a) and timelag between the 95 % of the maximum increase in discharge and groundwater (t_{peakQ}) (b) for all 133 events as a function of Topographic Wetness Index. The distinct outlier with a $t_{peakP} > 500$ min and $t_{peakQ} > 300$ min is situated in a hollow with an upslope contributing area of > 0.1 ha. Grey bar: inter quartile range, dot: median for each site, black line: LOWESS curves fitted to the median values, r_s : Spearman Rank Correlation Coefficient and associated p-value.

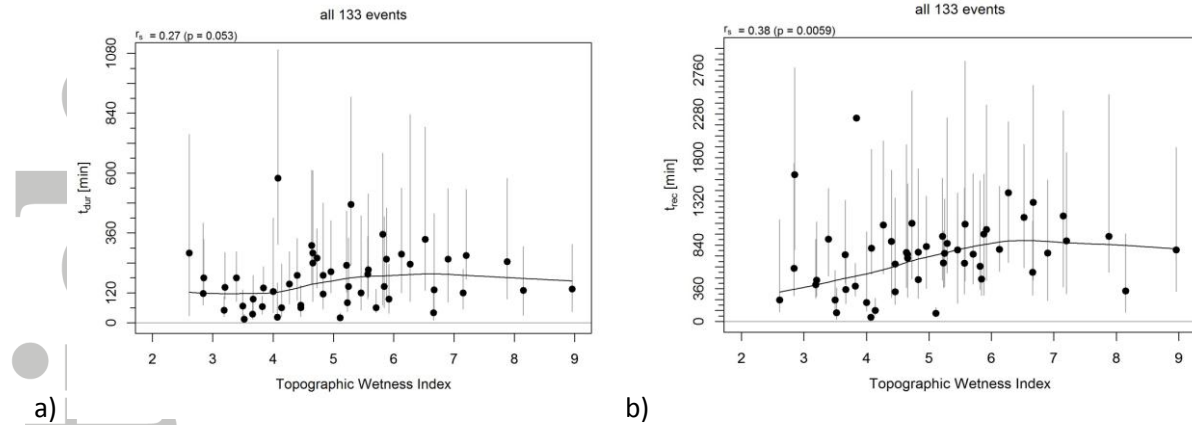


Fig. 9 The groundwater peak duration (t_{dur}) (a) and duration of the groundwater recession (t_{rec}) (b) for all 133 rainfall events and all sites plotted as a function of the Topographic Wetness Index. Grey bar: inter quartile range, dot: median for each site, black line: LOWESS curves fitted to the median values, r_s : Spearman Rank Correlation Coefficient and associated p-value.

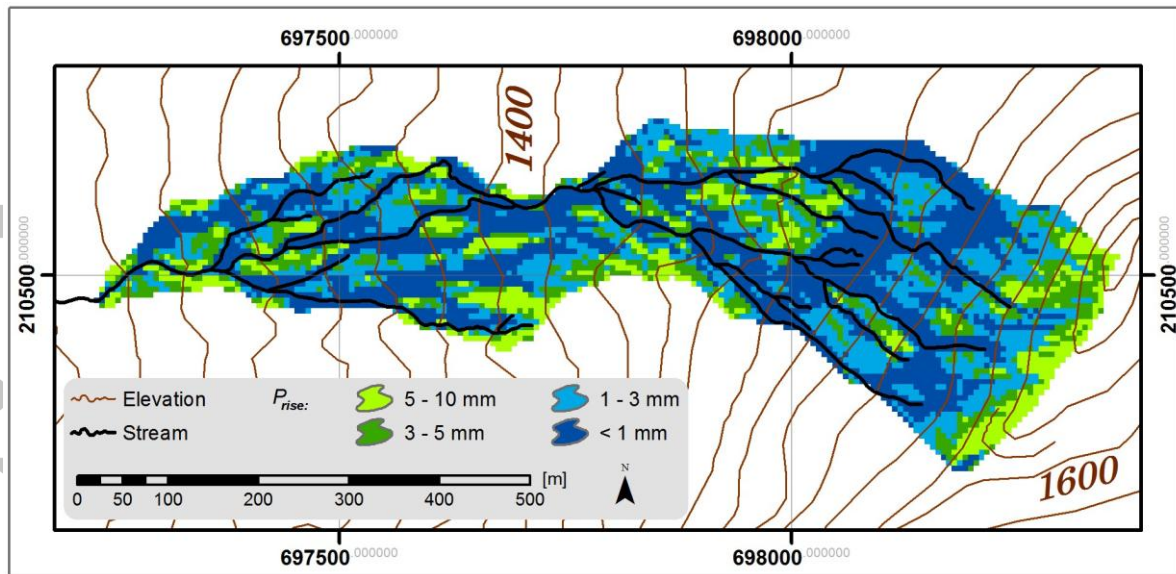


Fig. 10: Spatial distribution of an expected groundwater response after 1 mm, 3 mm, 5 mm and 10 mm of cumulative rainfall based on the relationship median P_{rise} and TWI in Fig. 6. Note that this pattern does not account for events that did not cause a response at all and neglects the effect of rainfall interception. (background-topographic map: Swisstopo, 123456789)